

UNIVERSITY OF GLASGOW

DEPARTMENT OF
AERONAUTICS & FLUID MECHANICS

AN INVESTIGATION INTO THE
THREE-DIMENSIONAL STALL DEVELOPMENT ON
A MODIFIED NACA 23012 AEROFOIL

by

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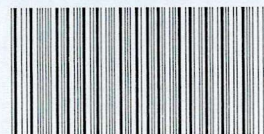


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1. INTRODUCTION

Reference 1 proposed a numerical method of modifying the trailing edge upper surface pressure gradient of a given aerofoil in a prescribed manner. The method was successfully applied to the NACA 23012 aerofoil, and the subsequent aerofoil designed which enhanced the trailing edge pressure gradient, built and tested in the Handley Page subsonic wind tunnel at the University of Glasgow. This modified NACA 23012 profile was designated GU 23012B (see Fig. 1).

A flow visualisation technique, using a fluorescent yellow "dayglo" oil-film, was used to indicate transition regions, laminar separation bubbles and the positions of turbulent separation. The extent of three-dimensionality, reverse flow and corner flow separation were also observed. Using this technique an insight into the applicability of the method of Ref 1 was obtained.

A detailed description of the static behaviour of the NACA 23012, tested in an identical manner, is given in Ref 2.

2. MODEL CONSTRUCTION

The NACA 23012 aerofoil was of a 0.55m chord and a 1.613m span. It was constructed of wood laminations on a steel spar and had an aerodynamically smooth surface. The GU 23012B was constructed in two halves each of which was a composite of glass fibre (approx. 3mm thick) and balsa wood (see Fig. 2). The glass fibre was hand laid in an open mould which took the form of a wax block cut to the exact negative of the required profile. The two halves were then bonded together. Each end was then recessed to accommodate an aluminium mounting plate which was subsequently bonded in place. The model was then rubbed down and polished to give an aerodynamically smooth surface of high quality.

3. TESTING PROCEDURE

The adopted flow visualisation technique followed that of Ref 2, and utilised a mixture of saturn-yellow "dayglo" powder and ondina oil applied to the surface of the model. The flow pattern was illuminated by ultraviolet light causing the pigment to fluoresce in the visible range. Good black and white photographic contrast was obtained by filtering out the UV by means of a yellow filter. Each flow pattern was obtained after applying the oil, setting the model incidence and then raising the wind speed from zero to the test value. Since this series of tests were executed in an identical manner to those in Ref 2, the results suffer from the same effects of flow acceleration and downward bias oil-flow.

A consequence of the method of Ref 1 was that both NACA 23012 and GU 23012B aerofoils have chord lines that lie along the x-axis (see Fig 1). Under test conditions the angle of incidence can only be measured between the trailing edge and the geometric centre-line of the wind tunnel. Consequently a "camber induced angle of incidence" for the GU 23012B had to be calculated. It was found to be 0.4° . This was then subtracted from any given angle of incidence measured from the trailing edge.

4 STALL DEVELOPMENT ON THE GU 23012B AEROFOIL

Figure 3 shows the flow development on the GU 23012B aerofoil at various angles of incidence at a Reynolds number of 1.5×10^6 . Up to an incidence of 10.95° the flow was closely two dimensional and it was noted that the boundary layer underwent a laminar to turbulent transition which moved towards the leading edge with increasing incidence. At 12.05° the boundary layer began to separate asymmetrically, from the trailing edge, with a tendency towards a larger separation region over the lower half span. At angles greater than 12.6° this asymmetry became significant and three-

dimensional flow increased. Two vortices developed on the upper surface at 15° forming two "stall cells".² The flow pattern became symmetrical with the cells keeping the flow symmetry with respect to the mid-span. These vortices tended to keep the mid-span region separated, while inducing the outer portions to remain attached. Figure 3(i) clearly shows these two vortices. Angles from 15.3° and above had stable symmetrical separation fronts and the two vortices were still present at 20° where 90% of the flow was fully separated.

It was observed that as the angle of incidence was increased, the laminar separation bubble moved closer to the leading edge and diminished in size. However, it remained present throughout the stall and even existed when the flow was fully separated at 25.5° (Fig. 3(1)).

The overall flow behaviour seemed to indicate that the GU 23012B had a trailing edge turbulent boundary layer stall characteristic similar to that of the basic NACA 23012 section (Ref 2).

5. COMPARISON WITH STALL DEVELOPMENT ON THE NACA 23012 AEROFOIL

When the present results were compared to those stated in Ref 2, the following differences were:

- (i) The increased stability of the flow separation front at any given angle of incidence.
- (ii) The constancy in advancement of the separation front towards the leading edge.
- (iii) At any given angle of incidence above 12° the degree of separation was greater than that of the NACA 23012. Assuming that the laminar flow region, over the leading edge, was similar to that of the NACA 23012 this would indicate that the modified section had a more severe adverse pressure gradient over its rear upper surface.

The unsteady periodic movement of the separation front at 14.2° and the sharp stall reported in Ref. 2 did not seem to be characteristic of this modified section.

Since the extraction of a separation point from flow visualisation photographs is highly subjective, existing NACA 23012 data were taken from Ref. 3. These data took the form of Hot film and pressure plots. Subsequent combination of these results with those obtained by flow visualisation² gave the "best fit" separation line shown in Fig 6. These data were then compared with the flow visualisation results for the GU 23012B which are shown in Fig. 7.

The design criterion used in Ref 1 was that the leading edge geometry was "not to be significantly altered". A consequence of this was that at high angles of attack the oncoming flow would "see" the same profile as the NACA 23012. It was therefore expected to give similar trailing edge separation characteristics as the NACA 23012. This is clearly shown in Fig. 7, where from about 17° upwards the two separation lines converge.

Although the GU 23012B was not tested at a higher Reynolds Number it was interesting to compare the present results with those obtained for the NACA 23012 at a Reynolds Number of 1.85×10^6 . A noticeable resemblance was observed. The main features of which were: (i) the tendency for enhanced separation over the lower span, (ii) the presence of two "stall cells", and (iii) a higher degree of flow symmetry.

It is well known that according to the classification of Gault⁴ the NACA 23012 aerofoil is problematic in respect to its stalling characteristics as it lies on the boundary between two types. Over a range of Reynolds Numbers the aerofoil might have a gradual trailing edge type stall or at some higher Reynolds Number, it may exhibit a combined leading and trailing edge stall. It is therefore not unreasonable to speculate that since the

GU 23012B is a modification of the NACA 23012 it too will be highly Reynolds Number dependent.

(6) COMPARISONS BETWEEN THEORY AND EXPERIMENT

Although the inverse aerofoil design method of Ref 1 did not include any boundary layer or wake interaction calculations, the obtained results discussed here indicate that the method may provide a good first approximation to an aerofoil with certain prescribed separation characteristics.

The boundary layer program used in Ref 1 was subsequently found not to give a good representation of the separation characteristics above an incidence of 13° (see Fig. 8). However, this program was only used to compare any one designed profile with the original NACA 23012, and Fig. 9 shows that there was an underestimation in the change in separation characteristics at low angles of incidence but an overestimation at higher angles. It also shows that for angles greater than 17° the predicted separation points of both NACA 23012 and GU 23012B converge. This appears to agree particularly well with those observations described in section (5) of this report.

7 CONCLUSIONS

The inverse aerofoil design method discussed in Ref 1 can provide a good first approximation to an aerofoil with certain prescribed separation characteristics. After successful application of this method to the NACA 23012 the resulting profile was observed to have enhanced boundary layer separation. However, the change was relatively small and under dynamic conditions its influence on the final outcome is doubtful.

It has already been validated¹ that this method can be used to design profiles which have a much greater reflex camber than that of the GU 23012B

and another variation on the NACA 23012 has been designed. It is hoped that this new profile will give the required amount of trailing edge separation that may allow further investigation into its effects on dynamic stall onset.

Acknowledgements

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3. Leishman, J.G. "Contributions to the experimental investigation and analysis of aerofoil dynamic stall", Ph.D Thesis, Glasgow University, March 1984.
4. Gault, D.E. "A correlation of low-speed airfoil section stalling characteristics with Reynolds Number and airfoil geometry", NACA TN 3963, 1957.

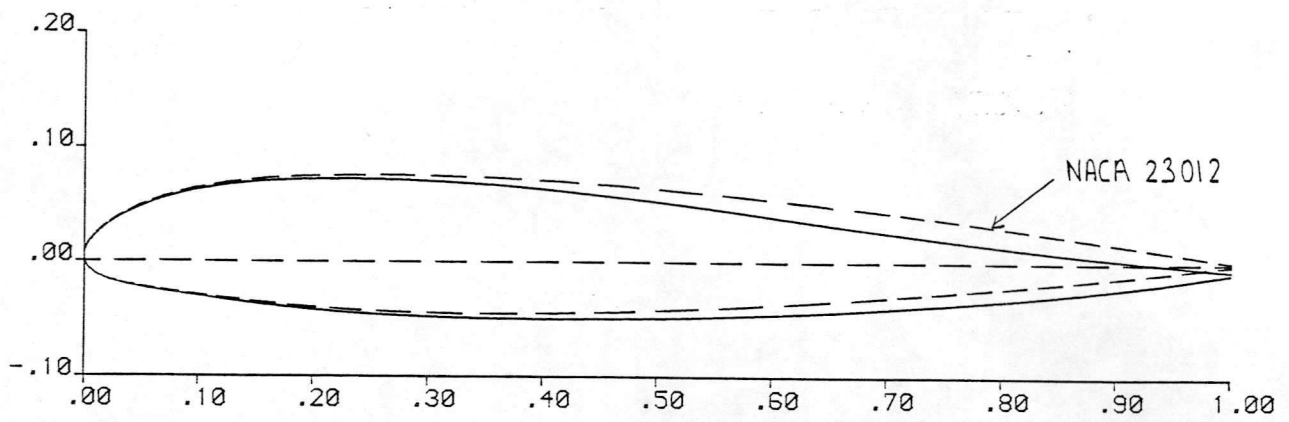


Figure 1. Profile Plots For NACA 23012 And GU 23012B

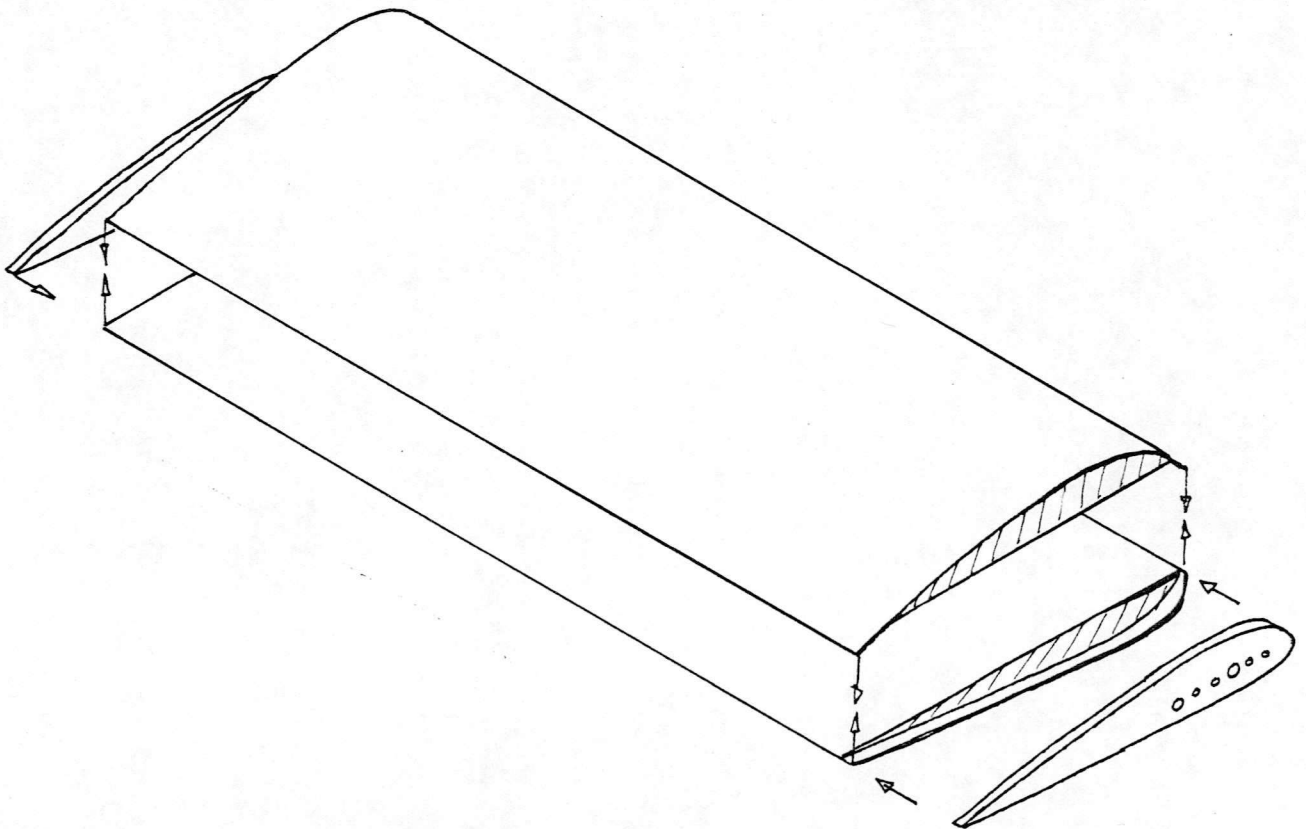
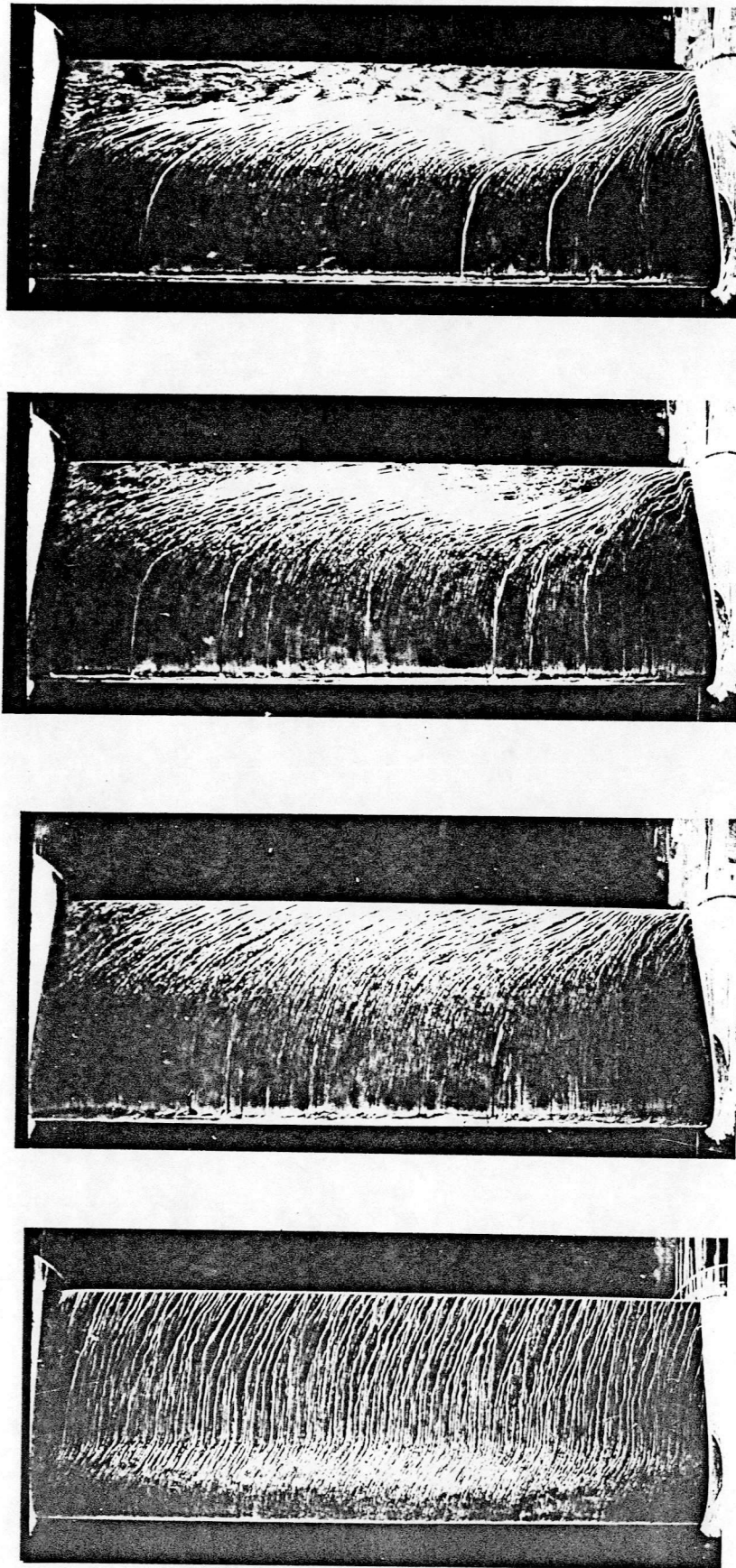
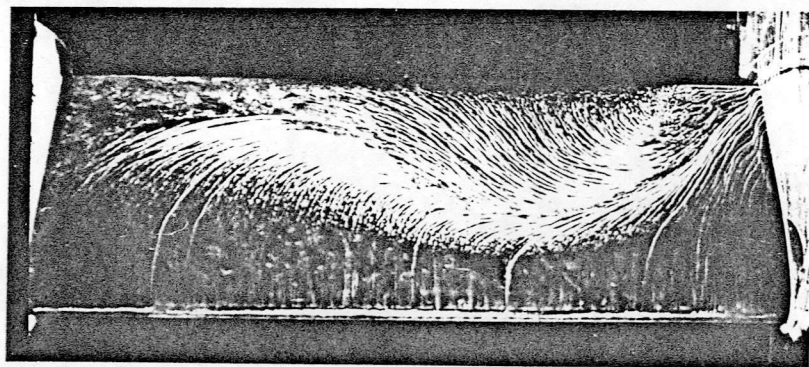


Figure 2. Construction Of The GU 23012B

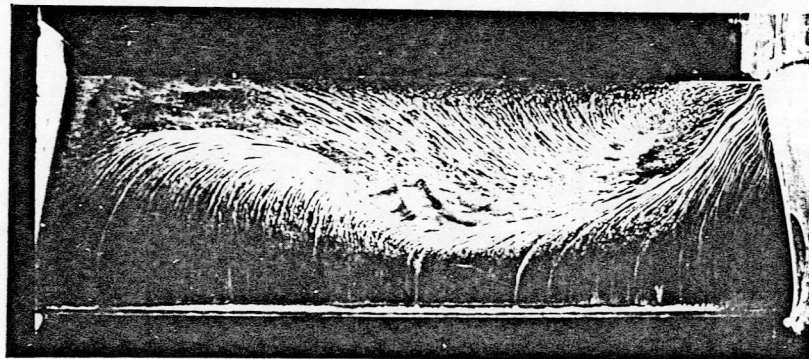


a) 4.3° b) 10.95° c) 12.05° d) 12.6°

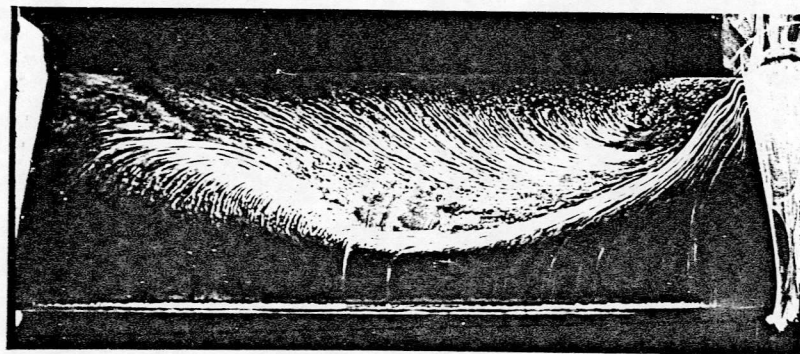
Figure 3. Surface Oil-Flow Photographs : GU 23012B Section, 0.55m chord
Re, No. = 1.5×10^6



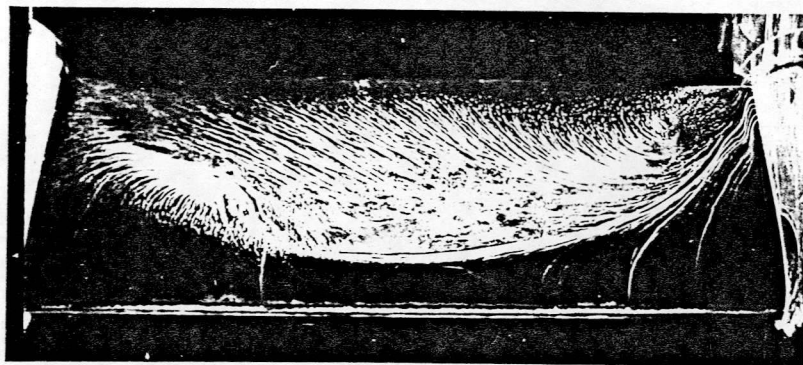
e) 13.2°



f) 13.8°

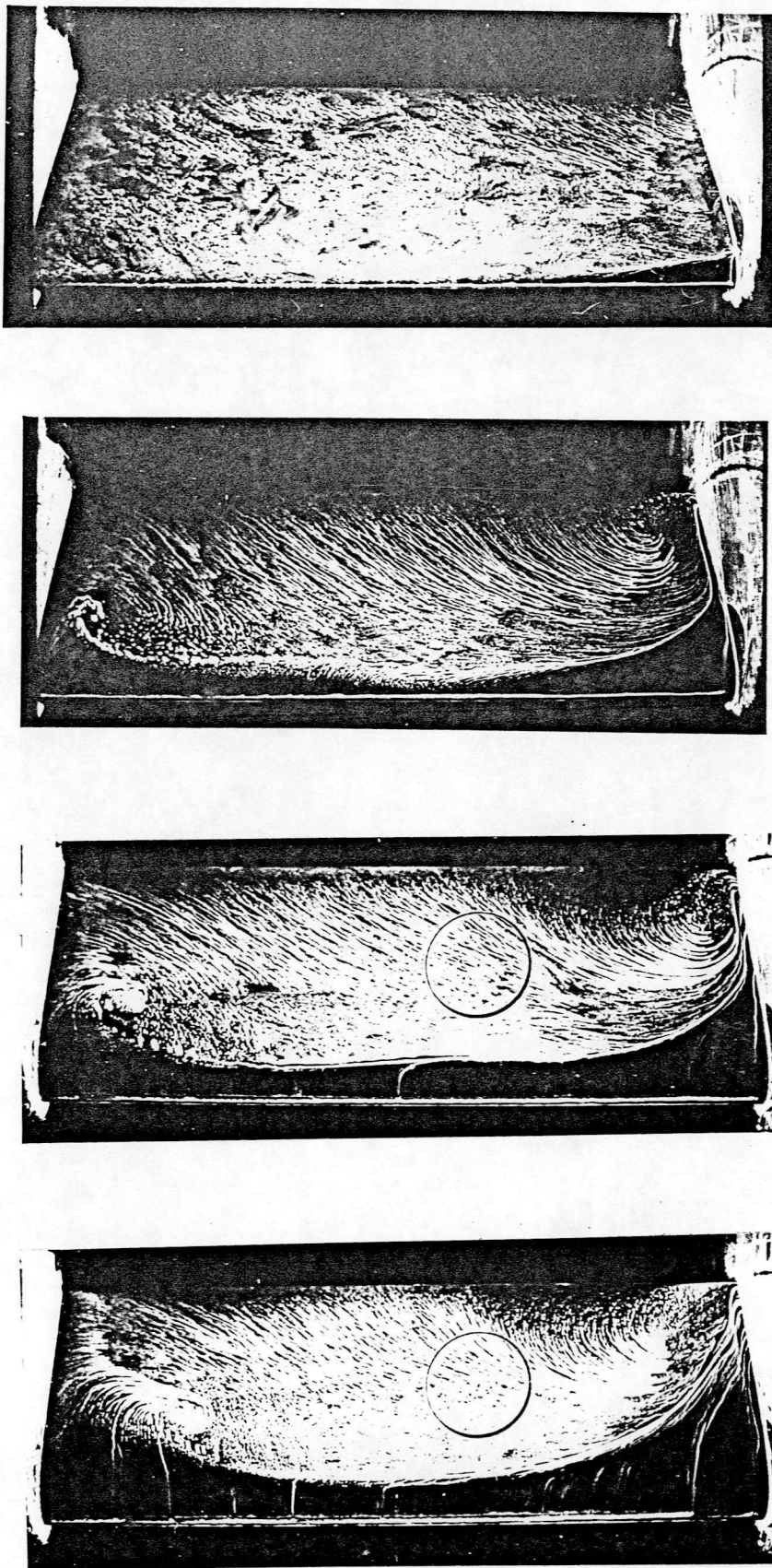


g) 14.4°



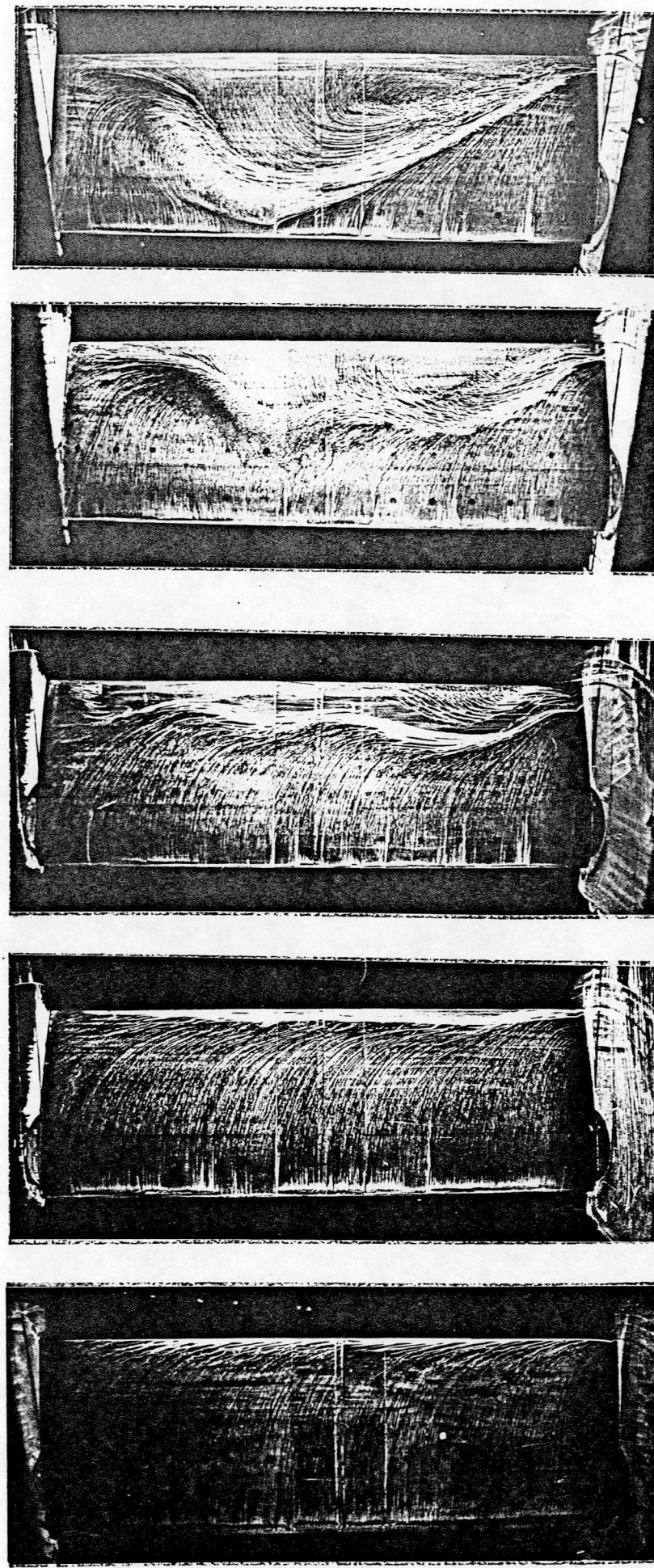
h) 15.3°

Figure 3. Surface Oil-Flow Photographs : GU 23012B Section, 0.55m chord
Re. No. = 1.5×10^6



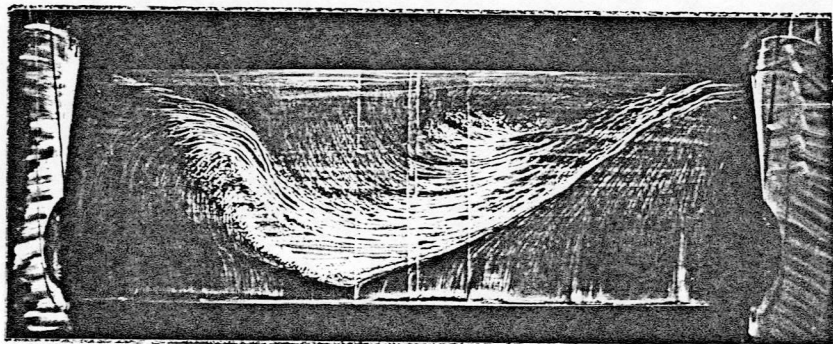
i) 16.2° j) 18° k) 20° l) 25.5°

Figure 3. Surface Oil-Flow Photographs : GU 23012B Section, 0.55m chord
Re. No. = 1.5×10^6

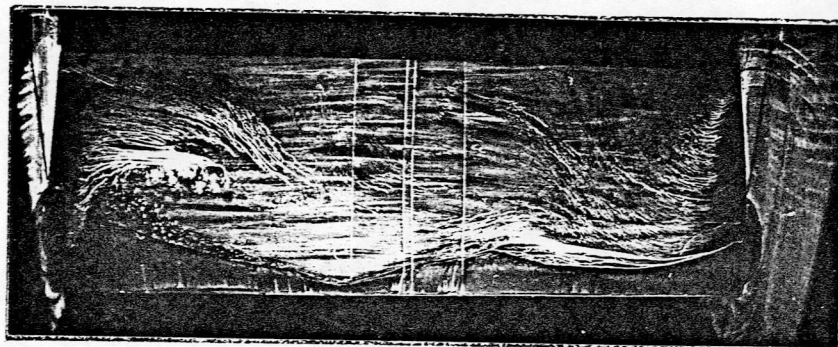


a) 10° b) 12° c) 14° d) 14.2° e) 15°

Figure 4. Surface Oil-Flow Photographs : NACA23012 Section, 0.55m chord
Re No. = 1.45×10^6

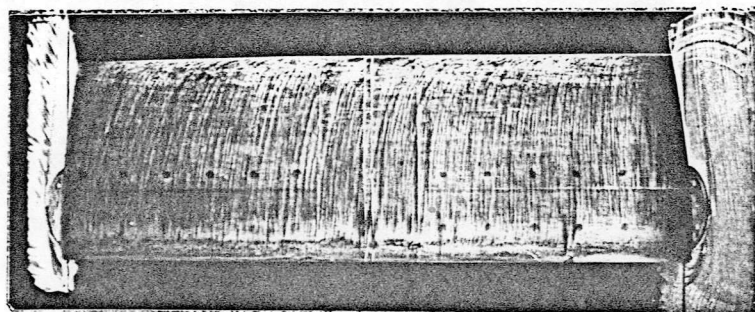


f) 16°

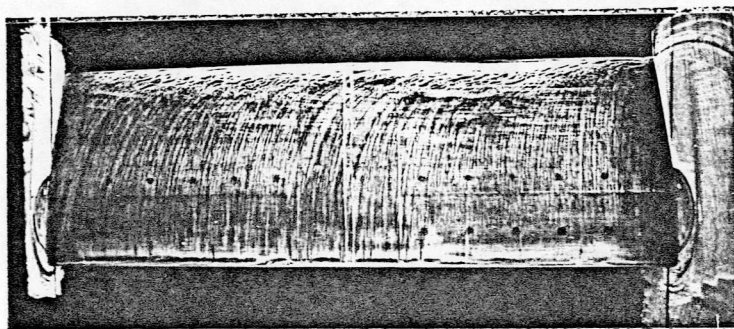


g) 20°

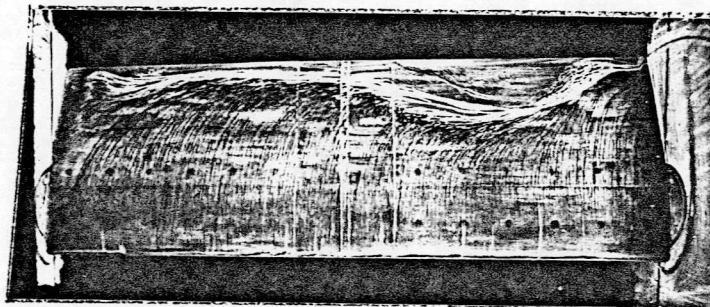
Figure 4. Surface Oil-Flow Photographs : NACA23012 Section, 0.55m chord
Re No. = 1.45×10^6



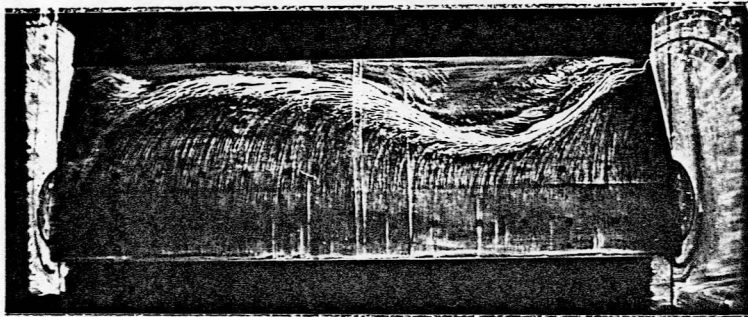
a) 8°



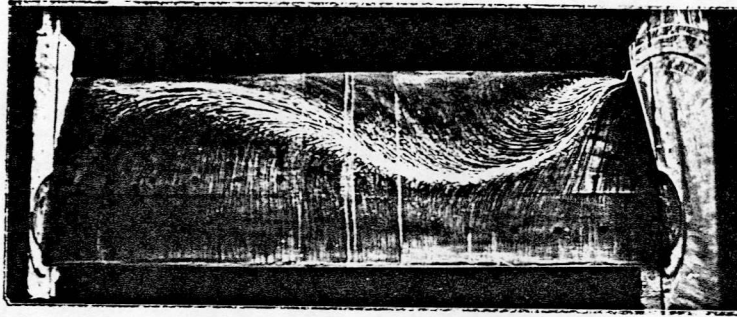
b) 12°



c) 14°



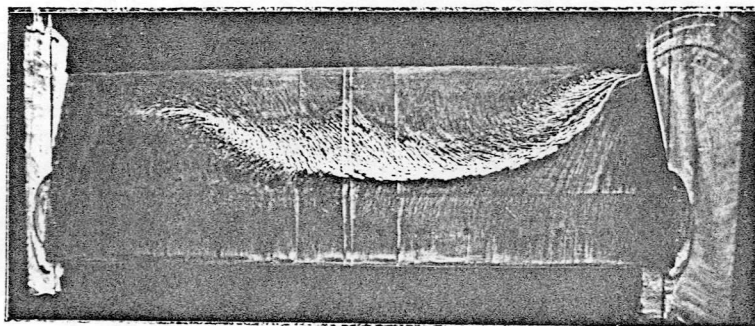
d) 14.2°



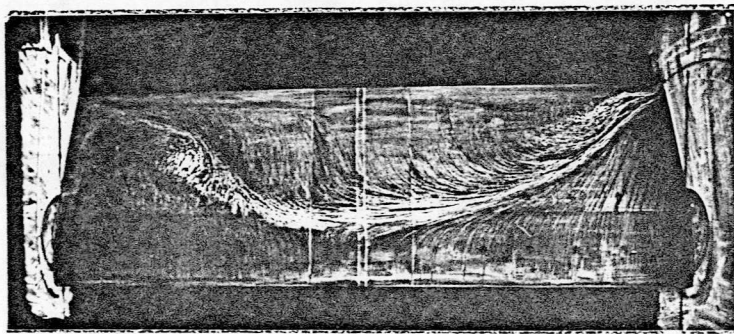
e) 14.5°

Figure 5. Surface Oil-Flow Photographs : NACA23012 Section, 0.55m chord

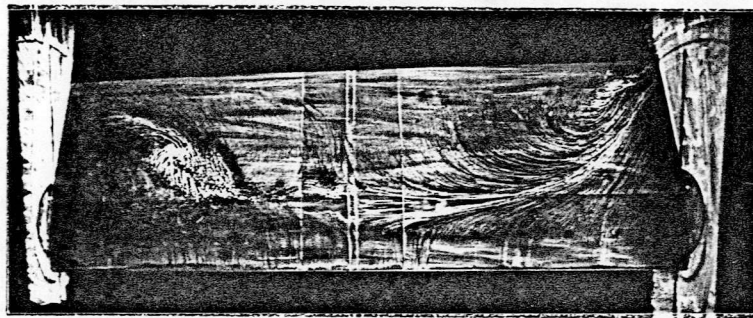
Re No. $\approx 1.85 \times 10^6$



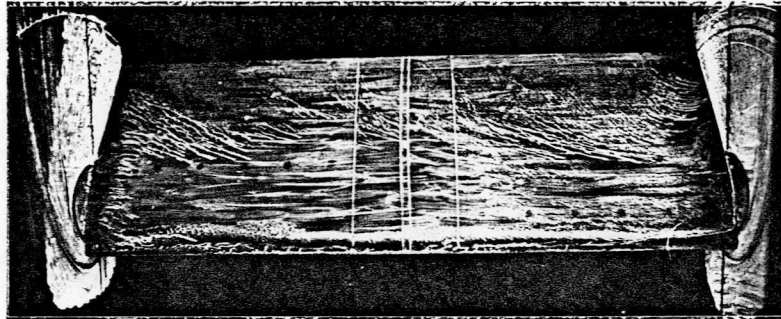
f) 15°



g) 16°



h) 18°



i) 25°

Figure 5. Surface Oil-Flow Photographs : NACA23012 Section, 0.55m chord

Re No. = 1.85×10^6

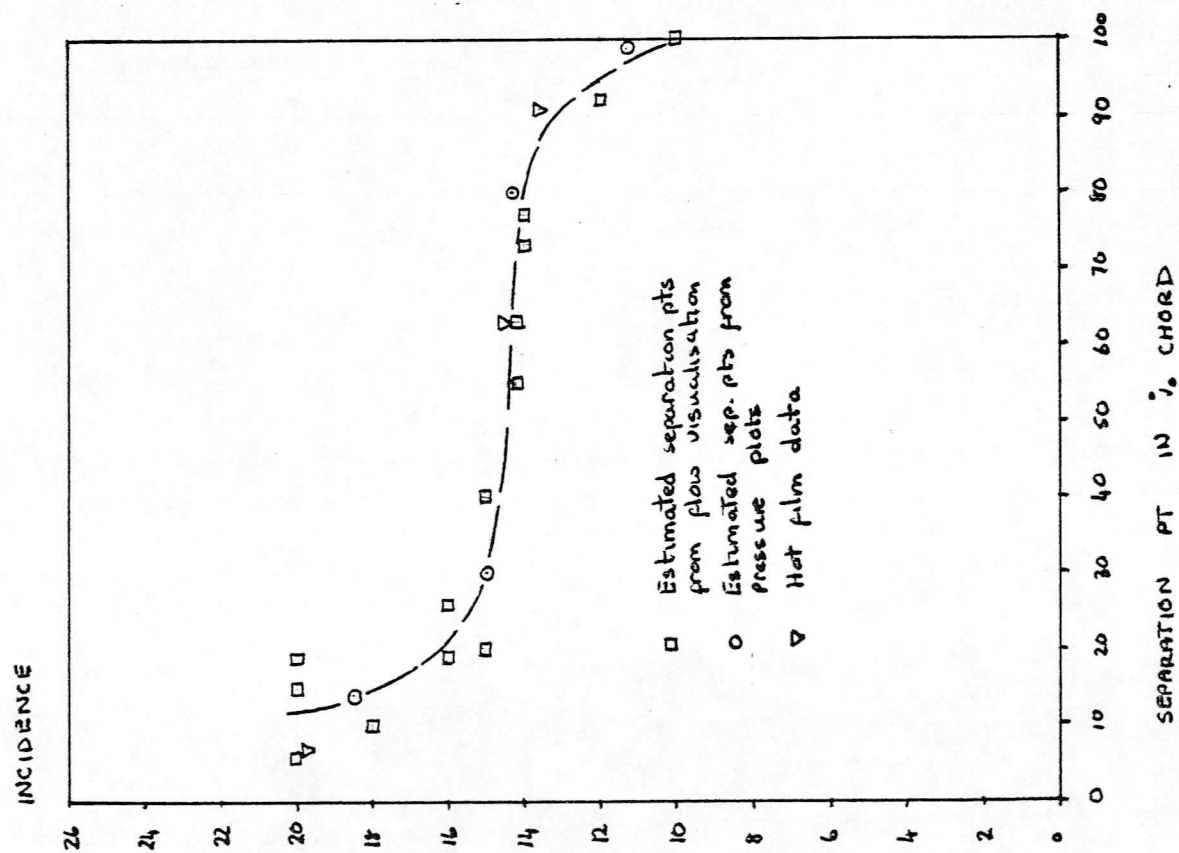


Figure 6. Locus Of Trailing Edge Flow Separation Points For The NACA 23012

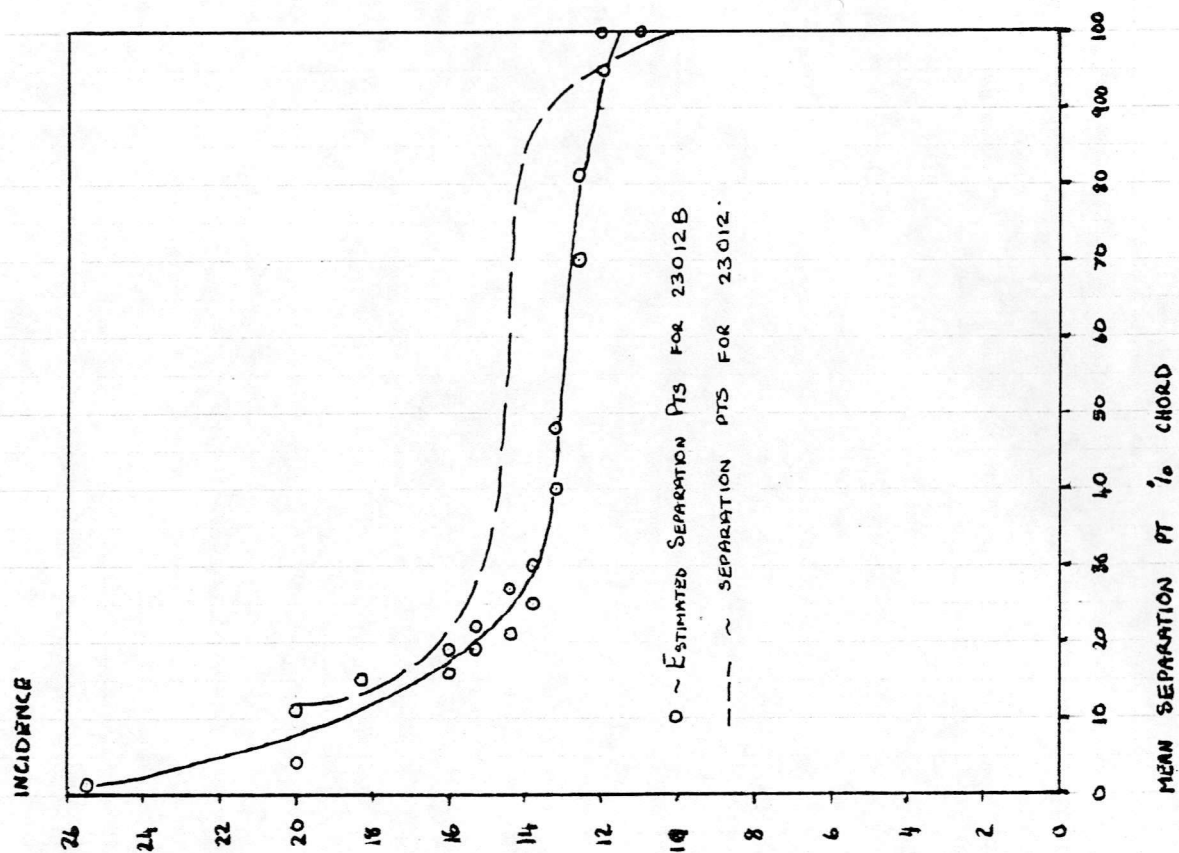


Figure 7. Locus Of Trailing Edge Flow Separation Points For The GU 23012B

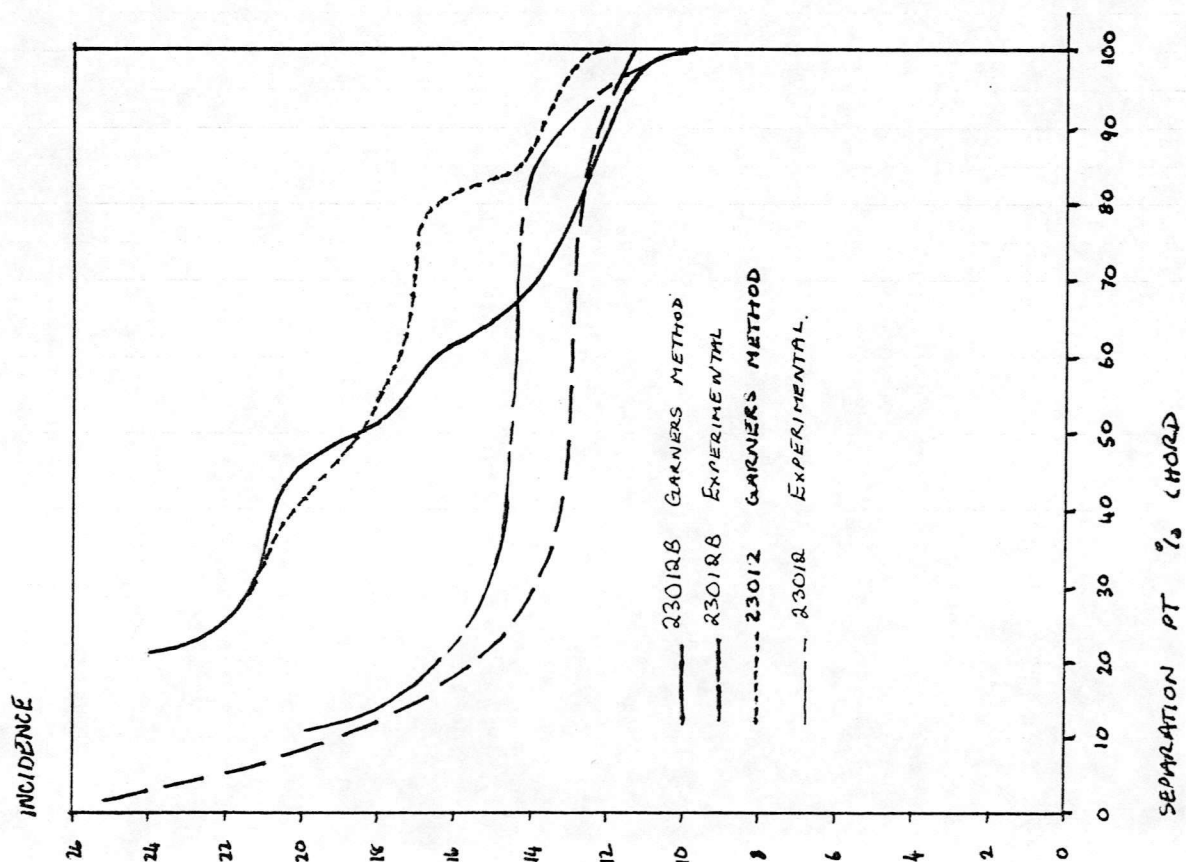


Figure 8. Comparison Between Predicted And Observed Flow Separation Points

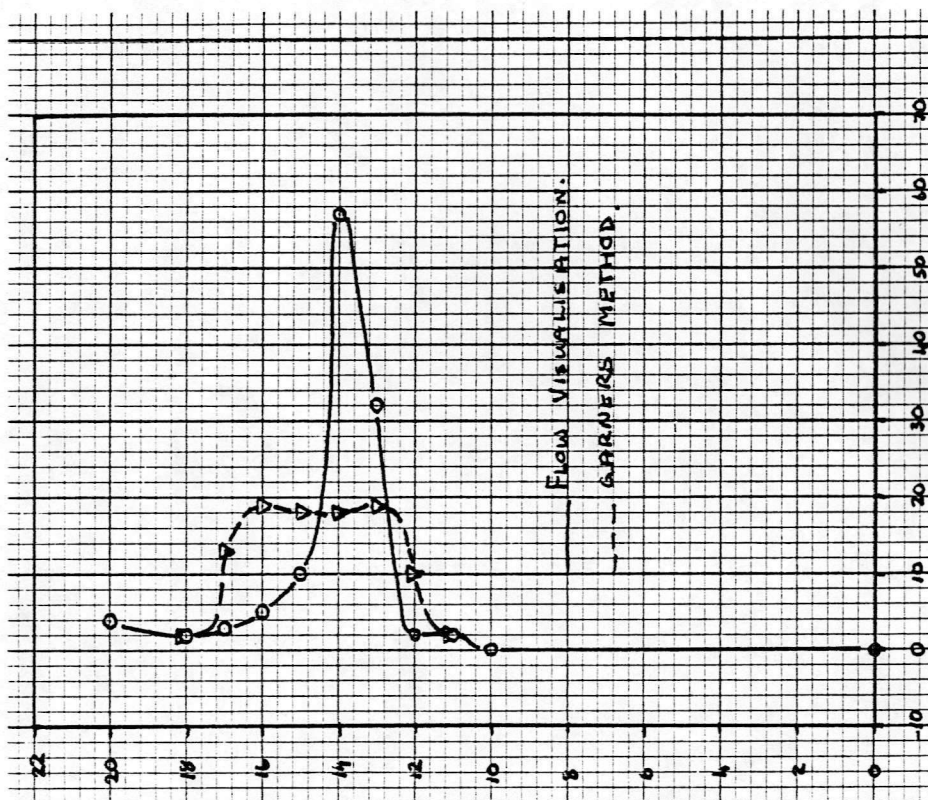


Figure 9. Absolute Percentage Difference In Predicted And Observed Separation Points



